International Journal of Sustainable Built Environment (2016) 5, 277–287

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International Journal of Sustainable Built Environment

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Original Article/Research

Mechanical and durability properties of fly ash geopolymer concrete containing recycled coarse aggregates

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Received 17 March 2016; accepted 29 May 2016

Abstract

This paper presents mechanical and durability properties of geopolymer concrete containing recycled coarse aggregate (RCA). The RCA is sourced from local construction and demolition (C&D) waste in Perth, Australia. The RCA is used as a partial replacement of natural coarse aggregate (NCA) in geopolymer concrete at 15%, 30% and 50% by wt. which corresponds to series two, three and four, respectively, while the geopolymer concrete containing 100% NCA is control and is considered as the first series. Class F fly ash is used as the source material for the geopolymer and 8 M sodium hydroxide and sodium silicate alkali activators are used to synthesise the fly ash geopolymer in this study. In all four series a constant alkali activator to fly ash ratio is used. Compressive strength, indirect tensile strength and elastic modulus of above geopolymer concrete are measured at 7 and 28 days, while sorptivity, immersed water absorption and volume of permeable voids of above geopolymer concrete are measured at 28 days. Relevant Australian standards are used to measure all the above properties except the sorptivity which is measured according to ASTM standard. Results show that the compressive strength, indirect tensile strength and elastic modulus of geopolymer concrete decrease with an increase in RCA contents, which is also true for both 7 and 28 days. Excellent correlations of compressive strength with indirect tensile strength and elastic modulus are also observed in geopolymer concrete containing RCA. Existing empirical models for cement concrete and geopolymer concrete containing NCA underestimate and overestimate the indirect tensile strength and elastic modulus, respectively of geopolymer concrete containing RCA. The measured durability properties such as sorptivity, water absorption and volume of permeable voids of geopolymer concrete were also adversely affected by the incorporation of RCA and these properties increase with an increase in RCA contents. The effects of RCA on the measured mechanical and durability properties of geopolymer concrete follow similar trend in cement concrete. Very good correlations of compressive strength with volume of permeable voids and water absorption of geopolymer concrete containing RCA are also observed, while the correlation between the compressive strength and the sorptivity is not that strong.

Keywords: Geopolymer; Fly ash; Recycled coarse aggregate; Construction and demolition waste; Mechanical properties and durability properties

1. Introduction

Concrete is the most widely used construction material in the world due to its low cost, excellent durability, easy availability of its constituent materials, easy formability to any shape, etc. Among all constituents of concrete

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Peer review under responsibility of The Gulf Organisation for Research and Development.

http://dx.doi.org/10.1016/j.ijsbe.2016.05.009
2212-6090/

ordinary Portland cement (OPC) is the main ingredient which binds the aggregates together. However, the manufacturing of OPC is an energy intensive process and the production of OPC is responsible for almost 5% of total global CO_2 emissions, which is the main cause of global warming (Malhotra and Mehta, 2002). In another estimate it was found that the production of one tonne of OPC releases approximately one tonne of carbon dioxide to the atmosphere (Malhotra and Mehta, 2002). Due to an increase in global population and urbanisation the increasing use of concrete in construction is unavoidable in near future. This concern has led to the use of new sustainable OPC less binder for concrete and supplementary cementitious materials (SCMs) as a partial replacement of a large amount of OPC in the concrete.

Additionally, extraction of natural aggregates is adversely affecting the natural eco system as the utilisation of concrete is increasing annually. On the other hand, the disposal of construction and demolition (C&D) wastes is also becoming a major environmental issue that has prompted many researchers worldwide to investigate new means of recycling it, with the aim of alleviating the pressure on the scarce landfill space available and also as a means to reduce the current reliance on natural aggregates and minerals (Kou et al., 2012; Tabsh and Abdelfatah, 2009; Zaharieva et al., 2003). Given that coarse and fine aggregates occupy 75–80% of the total volume of the concrete (Lamond and Pielert, 2006), the incorporation of C&D wastes in the form of recycled coarse aggregates (RCA) has huge potential (Corinaldesi and Moriconi, 2009). Although this is not a new concept, many researchers around the world have investigated the resulting properties and there is wide agreement that the concrete containing RCA presents inferior properties compared to conventional concrete incorporating natural aggregates (Corinaldesi and Moriconi, 2009; Etxeberria et al., 2007; Shaikh, 2013; Shaikh and Nguyen, 2013).

On the other hand, the Australian quarry industry estimates an average consumption of aggregate across Australia is about 160 million tonnes per annum; these figures are likely to increase due to the future developments of infrastructure (Aggregate industry report, 2012). The C&D industry contributes approximately 40% of total waste in landfills across Australia, and 90% of this waste is predominately concrete and masonry materials (Construction and demolition waste report, 2011). Meanwhile, the construction industry also produces 7.1% of Australia's greenhouse gasses indirectly through manufacturing, extraction, processing, and transportation of materials (Australian greenhouse office, 2010). Adopting recycled aggregates in concrete could help reduce the need to mine natural materials, both reducing waste and emissions. Thus, the incorporation of C&D waste as substitute to natural coarse aggregates (NCA) in concrete has many economic and environmental benefits to Australia's industries.

Geopolymer is an emerging cement less binder purported to provide a sustainable and environmentally friendly alternative to OPC. The term geopolymer was initially introduced by Davidovits (1991). Geopolymer is synthesised from materials of geological origin (e.g., metakaolin) or industrial by-products, such as fly ash and slag, which are rich in silica and alumina with alkaline activators. In one estimate it was found that the production of fly ash-based geopolymer requires approximately 60% less energy and has at least 80% less CO_2 emissions compared to the manufacture of OPC (Duxson et al., 2007). So far, extensive research and development on geopolymer concrete and composites have been undertaken worldwide with hopes to promote geopolymer as an ultimate sustainable construction material for the future (Wallah and Rangan, 2006; Sumajouw and Rangan, 2006; Kong and Sanjayan, 2010).

By adding the RCA as a partial or full replacement of NCA the sustainability of the existing geopolymer concrete containing natural aggregates can further be extended which together address the environmental issues of greenhouse gas emission by the manufacturing of OPC, the depletion of natural aggregate resources and the dumping problems of C&D wastes as landfill. Extensive research has been conducted on various mechanical and durability properties of geopolymer concrete containing natural aggregates and the same for OPC concrete containing recycled aggregates (Wallah and Rangan, 2006; Sumajouw and Rangan, 2006). However, a few researches on mechanical and durability properties of geopolymer concrete containing recycled coarse aggregates are reported (Sata et al., 2013; Nuaklong et al., 2016; Anuar et al., 2011; Shuang et al., 2012; Posi et al., 2013). Anuar et al. (2011) studied the compressive strength of geopolymer concrete containing recycled concrete aggregate, where the source material for geopolymer was waste paper sludge ash instead of popularly used fly ash and slag. Results show that the compressive strength is increased by about 10% from 7 days to 28 days and high molarity of sodium hydroxide shows higher compressive strength in geopolymer concrete. Shuang et al. (2012) evaluated the mechanical properties of geopolymer concrete containing 50% and 100% recycled coarse aggregate as a replacement of natural coarse aggregate and compared with those of ordinary concrete. Results show that the compressive strength and elastic modulus are all higher in the case of geopolymer concrete containing recycled coarse aggregate than its counterpart OPC concrete containing RCA and the above mechanical properties decrease with an increase in RCA contents. They also reported better interfacial transition zone in the case of geopolymer concrete than the OPC concrete. Recently, Posi et al. (2013) studied the mechanical properties of geopolymer concrete containing recycled lightweight aggregates and reported that similar to normal weight recycled coarse aggregate the compressive strength of geopolymer concrete decreases with an increase in recycled light weight aggregate contents. However, mixed results are reported on the modulus of elasticity in their study. Sata et al. (2013) also reported a study where crushed concrete and crushed brick were used as a replacement of natural coarse aggregates in geopolymer pervious concrete containing different concentrations of sodium hydroxide solution. Results show that the measured compressive and indirect tensile strengths are lower in geopolymer pervious concrete containing crushed concrete and crushed bricks as coarse aggregates are lower than their counterpart natural coarse aggregates. Results also show that the both compressive and indirect tensile strength of all three types of geopolymer concrete increase with an increase in the concentrations of sodium hydroxide solution. Nukalong et al. (2016) also reported a study on geopolymer concrete made by crushed concrete as coarse aggregates and reported reduction in compressive strength due to addition of recycled crushed concrete as coarse aggregate. This paper reports the effects of different RCA contents obtained from mixed construction and demolition waste on compressive strength, indirect tensile strength and elastic modulus of geopolymer concrete and compared with that of 100% NCA. Durability properties namely water absorption, volume of permeable voids, water sorptivity and chloride ion penetration of above geopolymer concrete containing RCA are also studied and compared with that of 100% NCA in order to evaluate the effects of various RCA on the durability of geopolymer concrete. Currently very few results exist on the durability properties of geopolymer concrete containing RCA. Even very limited results exist on the compressive strength and elastic modulus of geopolymer concrete containing RCA but they are based on different source materials, alkali activators, source of RCA, etc. This paper fills this gap and presents the mechanical and durability properties of geopolymer concrete containing RCA with the same mix proportion.

2. Materials, mix proportions and methodology

The class F fly ash used as source material in this study is obtained from Gladstone Power Station in Queensland, Australia which is used to form the geopolymer binder along with alkaline liquids. The chemical composition of fly ash is shown in Table 1. The activating alkali solution consisted of Na_2SiO_3 and NaOH solutions. The composition of Na_2SiO_3 is (wt.%): $Na_2O = 14.7$, $SiO_2 = 29.4$ and water = 55.9. The other characteristics of Na_2SiO_3 solution are: specific gravity = 1.53 g/cc, and viscosity at 20 °C = 400 cp. The NaOH solution is prepared from analytical grade NaOH pellets. The alkaline liquid is mixed 24 h prior to mixing of the concrete. The mass of Na_2SiO_3 used is 2.5 times that of the NaOH as past research (Hardjito et al., 2004) showed this to be the optimal ratio based on compressive strength.

Table 2
Properties of aggregates.

Properties measured		RCA	NCA
Water absorption (%)		4.9%	0.5%
Uncompacted bulk density (kg/m^3)		1181	1420
Compacted bulk density (kg/m^3)		1247	1522
Constituents of RCA (wt.%)			
Concrete	Brick	Asphalt	Other
75.0%	12.4%	6.6%	6.0%

The recycled coarse aggregate was obtained from a local construction and demolition (C&D) waste recycling plant in Perth, Western Australia. Table 2 shows the analysis of contents of a 5 kg sample of the C&D waste used as RCA in this study. Different materials in C&D wastes were hand-picked and separated according to respective types. They were then weighted and expressed in terms of mass percentages. It can be seen that approximately 75% are concrete and the rest consisted of masonry, tile, asphalt and others. Table 2 also shows the water absorption and density of recycled and natural coarse aggregates. Sieve analysis of RCA is also conducted and is shown in Fig. 1. It is observed that the RCA used in this study met the requirements specified in Australian standard (AS 2758.1). The natural coarse aggregates (NCA) used in this study were a mixture of 10 mm and 20 mm in size. The sieve analysis of NCA is also shown in Fig. 1. The NCA and RCA used in this study were in saturated and surface dry condition before being used in the mixing.

In this study, four series of mixes are considered. Table 3 shows the detail experimental programme and mix proportions of all four series. The first series is the control series where 100% NCA is used in geopolymer concrete and is designated as GPC0 mix. The rest three series are geopolymer concrete containing 15%, 30% and 50% (by wt.) RCA as a partial replacement of NCA. The alkali activator solution to fly ash ratio of all geopolymer concrete is kept similar. Conventional mixing is used to prepare the geopolymer concrete. First the fine and coarse aggregates including recycled coarse aggregates were dry mixed in the pan mixer for 1–2 min followed by the addition of class F fly ash to the mixer and dry mixed for further 2–3 min. Alkali solutions were then gradually poured into the mixer where they were wet mixed for further 2–3 min until uniform mixing is visually observed. The geopolymer concrete are subjected to steam curing at 60 °C for 24 h immediately after casting. The specimens are then demolded and cured in the laboratory in open air until the date of testing. Mechanical properties were measured at 7 and 28 days while the durability properties were measured at 28 days

Table 1
Chemical compositions of class F fly ash.

Compounds	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	MgO	P_2O_5	SO_3	TiO_2	MnO	LOI
Fly ash	51.11	25.56	12.48	4.3	0.77	0.7	1.45	0.885	0.24	1.32	0.15	0.57

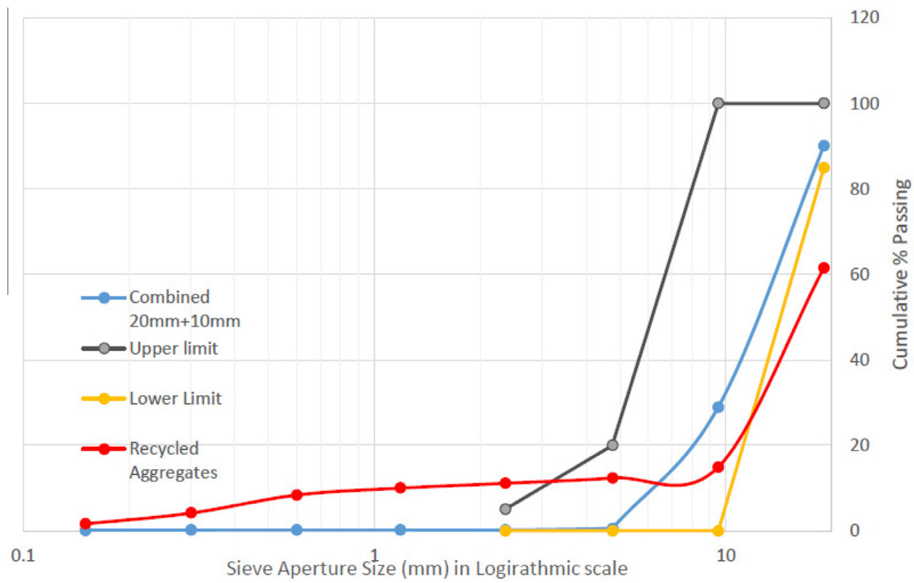

Figure 1. Sieve analysis of natural coarse aggregate and recycled coarse aggregate.

Table 3
Concrete mix proportions.

Mix proportion on kg/m^3				
Series	GPC0	GPC15	GPC30	GPC50
RCA replacement (%)	0	15	30	50
RCA (kg/m^3)	0	185	370	617
NCA (kg/m^3)	1233	1046	862	617
Fine aggregate (kg/m^3)	554	554	554	554
Fly ash (kg/m^3)	408	408	408	408
Sodium silicate	118	118	118	118
Sodium hydroxide (8 M)	47	47	47	47

only. Concrete cylinders having 100 mm in diameter and 200 mm in height were cast to measure the compressive strength and elastic modulus, while 150 mm diameter by 300 mm height cylinders were cast to measure the indirect tensile strength. In the case of durability property tests, concrete cylinders having 100 mm diameter and 200 mm height were also cast and then cut into three pieces each having 50 mm thickness. At least three specimens were cast and tested for each mix and each property. The compressive strength, indirect tensile strength and elastic modulus were measured according to Australian standards AS1012.9, AS1012.10 and AS1012.17, respectively. The 100 × 200 mm cylinders required for the compressive strength and modulus of elasticity were sulphur capped to ensure a smooth surface and improve test results. A Controls MCC8 3000 kN machine was used to test the compressive strength and indirect tensile strength of all concrete samples. For the determination of modulus of elasticity a DMG/Rubicon 2500 kN Universal Testing Machine was used to apply a constant load rate up to 40% of the ultimate load of respective concrete mix, while two linear variable differential transducers (LVDT) were used to measure the axial deformation of the cylinder. The slope of the recorded stress vs strain curve yielded the elastic modulus of the concrete.

The rate of water absorption (sorptivity) of concrete samples was determined at 28 days according to ASTM C1585-13 (ASTM, 2013). This test determined the rate of absorption of water by measuring the increase in the mass of a concrete specimen resulting from absorption of water as a function of time up to 8 days. The first 6 h rate of water absorption is used to determine the initial absorption of concrete known as "sorptivity" of the concrete, while the rate of water absorption from 1 day to 8 days is used to determine the secondary absorption. The volume of permeable void (VPV) test was conducted to estimate the percentage of voids present in the concrete specimens after 28 days of curing based on AS 1012.21:1999 (Standards Australia, 1999). The VPV is determined by boiling the 50 mm cut concrete specimens for at least 5 h in a water tank at 105 °C and weighing the sample in water, then measuring the percentage of voids with dried mass and mass in the water. The AS 1012.21-1999 is also used to determine the immersed water absorption of geopolymer concrete. The Sorptivity is an index of moisture transport into unsaturated specimens, and recently it has also been recognized as an important index of concrete durability (Dias, 2000). During sorptivity process, the driving force for water ingress into concrete is capillary suction within the pore spaces of concrete, and not a pressure head (Hall, 1989), while in immersed water absorption the driving force for water ingress into concrete is by a pressure gradient. The immersed water absorption also indicates total voids in the concrete. The chloride depth penetration test was conducted in accordance with the method proposed by Otsuki et al. (1993). The method is easy to perform and physically shows the penetration depth of chloride into concrete upon spraying with silver nitrate solution. Detail procedure can

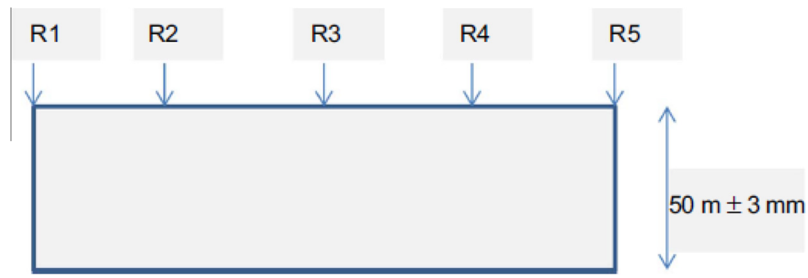

Figure 2. Locations of chloride ion penetration measurements made on each specimen.

be found in Otsuki et al. (1993) and in Shaikh et al. (2014) A minimum of two samples were prepared for each series. The samples were immersed in the solution for a total period of 28 d before the samples were taken out, cut in half and left to air dry under laboratory conditions. A 0.1 N silver nitrate solution was used to spray the cut surface of each slice as it was examined, to give the most distinctive colour change boundary – indicated by a white precipitate resulting from the formation of silver chloride on the surface and a brown colour where no chloride salt had penetrated. After spraying the samples, they were left overnight so that the colour change boundary was well defined; they were then marked out using a pen to allow the boundary to be more easily distinguished. Five readings were then made at the locations depicted in Fig. 2; these were then averaged to give the penetration depth of the chloride ions for each series.

3. Results and discussion

3.1. Mechanical properties

The effect of different RCA contents on compressive strength of geopolymer concrete is shown in Table 4. It can be seen that the compressive strength of geopolymer concrete containing 100% NCA is increased by about 9% from 7 to 28 days. Similar increase in compressive strength from 7 to 28 days is also reported in other studies e.g. by Ryu et al. (2013) and Anuar et al. (2011). It can also be seen that by increasing the RCA contents the compressive strengths at both ages decrease gradually however, at very low rate e.g. only 15% and 16% at 7 and 28 days, respectively for RCA content of 50%, which is slightly lower than OPC concrete containing 50% RCA of same type (e.g. Shaikh et al., 2014). A similar reduction by about 13% of 28 days compressive strength of OPC concrete containing 50% RCA is also reported by Xiao et al. (2005). It is also interesting to see that the maximum increase in compressive strength from 7 to 28 days is about 5% in the case of geopolymer concrete containing 50% RCA. It again shows consistency with other research results on negligible improvement on compressive strength of geopolymer concrete, because most of the geo-polymerisation reaction happens within the first few days of the curing in geopolymer concrete (Wallah and Rangan, 2006; Sumajouw and Rangan, 2006).

In the case of indirect tensile strength a very similar trend to that of compressive strength is observed, where it decreases with an increase in RCA contents (see Table 4). It can be seen in the table that the maximum reduction in 7 and 28 days indirect tensile strength is about 23% and 16%, respectively at RCA content of 50%. The effect of longer curing from 7 to 28 days is however, found to improve the tensile strength of geopolymer concrete containing RCA by about 11–21%. In the case of OPC concrete containing 50% RCA of same type, it has been found that the 7 and 28 days indirect tensile strength is dropped by about 30% and 23%, respectively in Shaikh et al.'s study (2014). The lower reduction in indirect tensile strength of geopolymer concrete containing 50% RCA compared to its counterpart OPC concrete containing the same amount of RCA could be the good bond of the geopolymer binder with the RCA. It is also reported that the bond strength of geopolymer with concrete and steel is higher than that of OPC concrete (Provis and van-Deventer, 2009; Sarker, 2010). Shuang et al. (2012) also reported denser interfacial transition zone (ITZ) in geopolymer concrete containing RCA than the OPC concrete containing RCA. The effect

Table 4
Mechanical and durability properties of geopolymer concretes containing various RCA contents as a partial replacement of NCA.

Series	Compressive strength (MPa)		Indirect tensile strength (MPa)		Elastic modulus (GPa)		Volume of permeable voids (%)	Sorptivity (mm/s^0.5)	Absorption (%)	Chloride ion penetration depth (mm)
	7 days	28 days	7 days	28 days	7 days	28 days	28 days	28 days	28 days	28 days
GPC0	41.1	45.3	3.9	4.4	23	24	11.3	0.026	4.9	11.1
GPC15	40.6	41.8	3.7	4.1	21	20	11.8	0.023	4.8	18.6
GPC30	37.4	37.6	3.1	3.9	17	15	13.7	0.028	5.6	21.1
GPC50	35.0	36.8	3.0	3.7	16	14	14.3	0.033	5.9	25.5

of RCA on the elastic modulus of geopolymer concrete is also evaluated and is shown in Table 4. It can be seen in the figure that the elastic modulus decreased with an increase in RCA contents, which is consistent with Shuang et al.'s (2012) study on the elastic modulus of geopolymer concrete containing RCA. The maximum reduction of modulus of elastic of the present study was about 42% in the case of geopolymer concrete containing 50% RCA, which is also consistent with results reported by Xiao et al. (2005) for OPC concrete containing 50% RCA. Interestingly, after 28 days instead of slight improvement in elastic modulus in the case of geopolymer concrete containing 100% NCA, a slight reduction is observed in all geopolymer concrete containing RCA in this study. The reason is not clear but the weak and porous RCA could be the reason for this reduction which is discussed in the following section.

The experimentally measured indirect tensile strength and elastic modulus are also compared with existing empirical models. In Fig. 3 it can be seen that the indirect tensile strengths predicted by AS3600 (2009) and by Ryu et al. (2013) are much lower than the measured values. This difference could be due to two reasons. The empirical model proposed in AS3600 is for OPC concrete containing natural aggregates and the model proposed by Ryu et al. (2013) is for geopolymer concrete containing natural aggregates. Currently no model exists to predict the tensile strength of geopolymer concrete and even that containing RCA. The big discrepancy could be due to difference in binder types (OPC vs geopolymer) and the aggregate types (natural vs recycled). On the other hand, the discrepancy between Ryu et al.'s model and the measured tensile strength could also be due to difference in molarity of NaOH solution (8 M in current study vs 9 M used by Ryu et al.) and the mass ratio of Na_2SiO_3/NaOH (2.5 used in current study vs 1 used by Ryu et al.). Research shows that (Hardjito and Rangan, 2005; Shaikh, 2014) the strength of geopolymer is increased when the Na_2SiO_3 content is increased. Therefore, using geopolymer concrete containing high Na_2SiO_3/NaOH ratio the proposed empirical model is expected to be different and hence, further research in also needed for different Na_2SiO_3/NaOH ratios in the empirical model.

The measured elastic modulus of geopolymer concrete containing RCA is also compared with existing model and is shown in Fig. 4. It can be seen that the AS3600 which is for OPC concrete containing natural aggregates and the empirical model proposed by Diaz-loya et al. (2011) for geopolymer concrete containing NCA overestimate the elastic modulus values. The RCA is believed to be the reason for huge difference. The RCA is generally sourced from crushed concrete structures, therefore, old mortars always adhered to the RCA. It is also known that in RCA the old adhered mortars are more porous than natural coarse aggregates and during the crushing and grinding process the RCA often contains micro-cracks (Etxeberria et al., 2006; Katz, 2004). Moreover, the interfacial transition zone (ITZ) between the old mortar and the old aggregate is also porous and weak (Otsuki et al., 2003; Poon et al., 2004). These factors adversely affect the modulus of elasticity of RCA. Research also shows that the porosity and cracks have detrimental effect on the elastic modulus of rock. The elastic modulus of rocks decreases as porosity increases (Zhang and Bentley, 2003; Al-harthi et al., 1999). Therefore, the elastic modulus of geopolymer concrete containing RCA is also expected to be smaller than that containing NCA which has been observed in this study. More research is also needed to establish empirical model to predict the elastic modulus of geopolymer concrete containing RCA. In this study relationships of

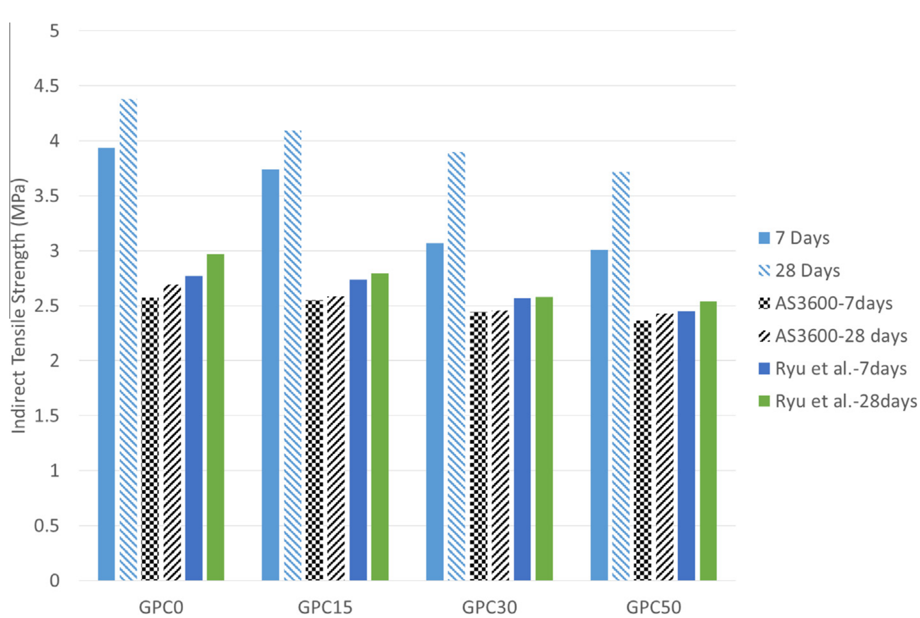

Figure 3. Comparison of measured indirect tensile strength of geopolymer concrete containing RCA and NCA with exiting models.

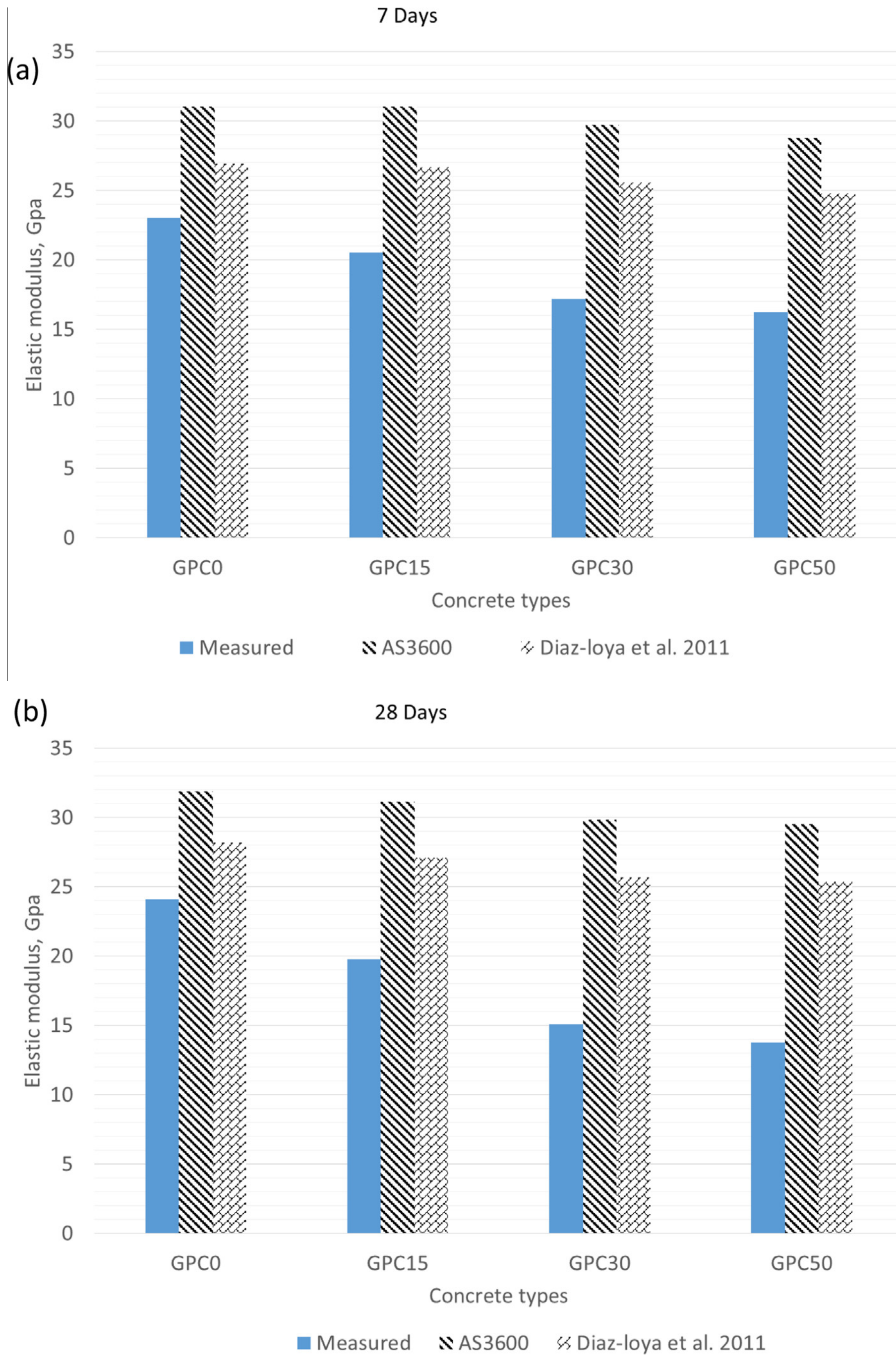

Figure 4. Comparison of measured elastic modulus of geopolymer concrete containing RCA and NCA at 7 and 28 days with exiting models.

compressive strength with indirect tensile strength and elastic modulus of geopolymer concrete containing RCA are also established and is shown in Fig. 5. It can be seen very good correlations, with R^2 vale of about 0.9, between the compressive strength and the indirect tensile strength and between the compressive strength and the elastic modulus, with an increasing trend of indirect tensile strength and elastic modulus with increase in compressive strength at both ages (see Figs. 5a and b). The trends are very similar to those reported in the case of OPC concrete and geopolymer concrete in many studies.

3.2. Durability properties

The rate of capillary absorption of water by concrete is a function of penetrability of pore system, where for unsaturated concrete the rate of ingress of water or other liquids is largely controlled by absorption due to capillary rise. In this study the rate of water absorption (sorptivity) of geopolymer concrete containing RCA are studied according to ASTM C1585-13 (ASTM, 2013). Fig. 6 shows the rate of water absorption of geopolymer concrete containing different amount of RCA as well as NCA for first six hours, which

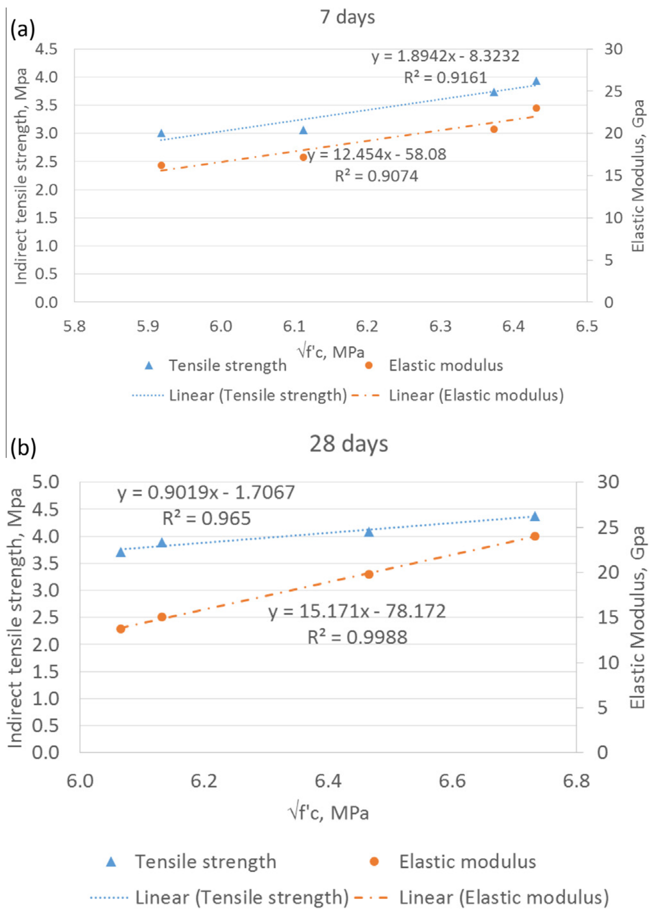

Figure 5. Correlation of compressive strength of geopolymer concrete containing RCA and NCA with indirect tensile strength and elastic modulus measured at 7 and 28 days.

is known as initial absorption. Correlation coefficient is also shown in the same figure where it can be seen that all series achieved at least $R^2 > 0.98$ according to ASTM C1585-13. It can also be seen that the rate of water absorption increased with an increase in RCA contents except the RCA content of 15% which is slightly lower than the geopolymer concrete containing 100% NCA. In the case of 50% RCA the sorptivity of geopolymer concrete is increased by about 26% which is much lower than that observed by Shaikh et al. (2014) in the case of OPC concrete containing the same amount and type of RCA. This increased absorption due to capillary rise is expected and is due to inferior properties of the RCA, such as higher water absorption than NCA (refer to Table 2). The higher water absorption of the RCA is primarily linked to the attached mortars on its surface which are very porous and also the presence of masonry products (see Table 2). Furthermore, given the nature of the RCA manufacturing process, it tends to form cracks and fissures in the aggregate which further contributes to increased sorptivity of the geopolymer concrete. The effect of RCA on secondary absorption of geopolymer concrete is shown in Fig. 7. The secondary absorption is measured from 1 to 8 days. It can be seen that the rate of water absorption becomes almost stable after about one day for all concrete. The results are also consistent with the rate of initial absorption, where it can be seen that the secondary absorption also increases with an increase in RCA contents and the rate of secondary absorption is about 32% higher at RCA content of 50%.

The effect of RCA on the immersed water absorption of geopolymer concrete containing different RCA contents can be seen in Table 4. It can be seen in the figure that, the water absorption of geopolymer concrete containing RCA increases with increase in RCA contents, with about 20% more water absorption at RCA content of 50%. This result is consistent with sorptivity and is due to the higher water absorption of RCA shown in Table 2 and the adherence of old mortars in the RCA which are generally more porous than the NCA. In the case of OPC concrete containing 50% RCA of same type, Ahmed (2013) reported

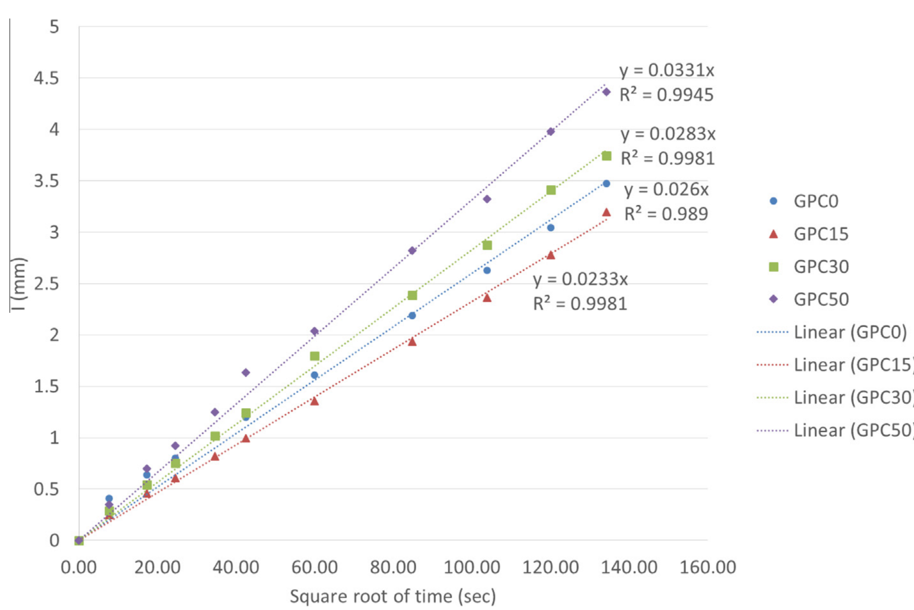

Figure 6. Initial rate of capillary absorption of geopolymer concrete containing RCA and NCA.

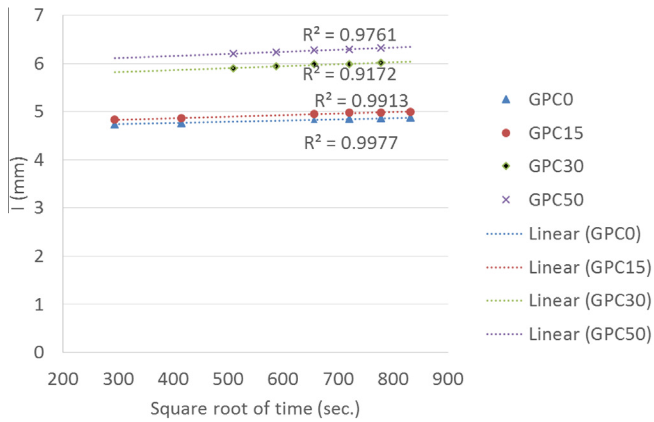

Figure 7. Secondary rate of capillary absorption of geopolymer concrete containing RCA and NCA.

much higher water absorption of about 42% more than the OPC concrete containing100% NCA.

The volume of permeable void (VPV) of concrete gives an indication of its durability related to permeability, absorption, etc. The results of VPV are affected by a number of factors including compaction, curing, air entrainment, absorption and physical nature of the aggregate used (AS 1012.21:1999 (Standards Australia, 1999)). The effect of RCA on the VPV of geopolymer concrete is shown in Table 4. It can be seen that the VPV in geopolymer concrete increases as the amount of RCA increases. The inferior properties of RCA are translated into the concrete specimens; it can be seen from the results that the VPV increases by 22% for geopolymer concrete containing 50% RCA, which is lower than the OPC concrete containing same amount and type of RCA reported by Shaikh et al. (2014), where VPV is increased by about 33%.

It can be seen that the measured water sorptivity, water absorption and volume of permeable voids of geopolymer concrete containing RCA are lower than OPC concrete containing the same amount and type of RCA. This shows that the pore structures, their distribution and total volumes of geopolymer matrix are much better than the OPC matrix. This coincides with the microstructural analysis results reported by Pan et al. (2013) where nanometre to micrometre scale pores were observed in fly ash geopolymer paste compared to irregular shape pores of a large number in the range of 0.05 to 10 microns in the OPC paste. The better ITZ of RCA with geopolymer paste reported by Shuang et al. (2012) than that with OPC paste is also the reason for observed better durability properties as well as better tensile strength of geopolymer concrete containing RCA than its OPC based counterparts.

Chemical attack on concrete structures is one of the primary reasons for its degradation, as a result of the ingress of chloride ions that penetrate into the concrete cover then chemically react to form rust around the reinforcement, spalling the concrete and causing a premature end to the structure's life cycle. It is claimed by some researchers that the chloride ion resistance of concrete depends largely on the porosity and inter-connectivity of the pore system and to a lesser extent on the chemical binding capacity of the cement (Thomas et al., 2013). In Table 4, it can be seen that upon the partial substitution of RCA, the geopolymer concrete is more susceptible to the ingress of ions; for the GPC15, GPC30 and GPC50 series, there is a 67%, 90% and 129% increase in chloride penetration depth relative to the control series. This decreased resistance was anticipated, given that RCA had higher water absorption (shown in Table 3) and porosity due to the adherence of mortar on the surface that is highly permeable, and also due to the masonry content, as can be seen in Table 2.

Observed compressive strength and durability properties of geopolymer concrete containing RCA are also correlated and are shown in Fig. 8. The figure shows that the sorptivity, water absorption and VPV decreases with an increase in compressive strength of geopolymer concrete containing RCA or in other words with a decrease in RCA contents. Very good correlations are observed in the case of VPV and water absorption with R^2 values of 0.9 and 0.8, respectively. However, in the case of sorptivity no strong correlation is observed partly due to the sorptivity test itself, because it does not represent the total porosity of the concrete instead it only represents pores a few millimetres (up to 5 mm) inside the surface of the concrete.

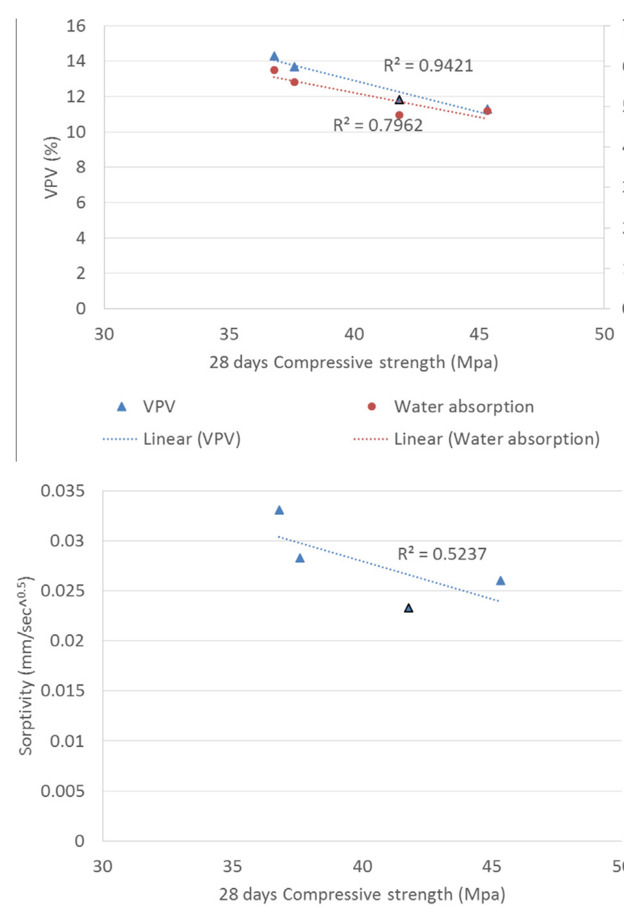

Figure 8. Correlations of 28 days compressive strength with durability properties of geopolymer concretes containing RCA.

4. Conclusions

This paper presents preliminary study on the effect of recycled coarse aggregates (RCA) on the mechanical and durability properties of fly ash geopolymer concrete. The mechanical properties are measured at 7 and 28 days while the durability properties are measured at 28 days. Based on limited mechanical and durability properties the following conclusions on the effect of recycled coarse aggregates on the mechanical and durability properties of geopolymer concrete can be made:

1. The inclusion of recycled coarse aggregate (RCA) as a partial replacement of natural coarse aggregates (NCA) in geopolymer concrete adversely affects its compressive and indirect tensile strengths and elastic modulus at both curing ages. The above properties decrease with an increase in the RCA contents. The results are also consistent with OPC concrete containing same type and amount of RCA. Interestingly, the elastic modulus of geopolymer concrete containing RCA at 28 days is slightly lower than those at 7 days.
2. The existing empirical models for geopolymer concrete containing NCA underestimates and overestimates the indirect tensile strength and elastic modulus, respectively of geopolymer concrete containing RCA. This indicates the necessity of more research in geopolymer concrete containing RCA to establish such empirical model for geopolymer concrete containing RCA. Very good correlations of indirect tensile strength and elastic modulus with compressive strength are observed in geopolymer concrete containing RCA at both ages.
3. The durability properties such as sorptivity, immersed absorption, chloride ion penetration and volume of permeable voids (VPV) of geopolymer concrete are also adversely affected due to inclusion of RCA. However, these properties are better than OPC concrete containing same amount and type of RCA. This better durability properties of geopolymer concrete containing RCA than the OPC concrete indicates refined microstructure of geopolymer paste than the OPC paste. Strong correlation of compressive strength with VPV and water absorption is also observed in this study.
4. This study also shows that the current sustainable concrete containing a partial replacement of OPC with supplementary cementitious materials and RCA as a partial replacement of NCA can further be extended to OPC less sustainable concrete with 50% less NCA without sacrificing much of the properties of current sustainable concrete.

Acknowledgments

Author gratefully acknowledges final year project students Swan Lin Hitet and Phng Zhen Tan for their help in casting and testing of the geopolymer concrete series in this study. Author also acknowledges the supports from Cement Australia and All Earth Group for donating class F fly ash and recycled coarse aggregates, respectively in this study.

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